

Augmented Reality-Based Zero-Error Approach for Improving the Training Process of a Cable Assembly Module in an Automotive Factory

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Abstract

With the rapid advancement of technology, the performance and usability of augmented reality (AR) have improved significantly, enabling its widespread adoption across various sectors such as education, healthcare, defense, automotive, aerospace, and aviation. By visualizing virtual objects and information within the physical environment, AR enriches user experience and makes training processes more effective and interactive. In the automotive industry, AR applications are predominantly utilized in design and manufacturing processes; although several augmented reality (AR) solutions have been proposed for wire harness assembly across diverse manufacturing sectors, implementing standalone, real-time feedback and dynamic error-logging mechanisms on mobile interfaces remains an area that requires further integration. This study aims to develop an AR-integrated system to minimize error rates in the electrical wiring harness assembly process of commercial vehicles at an automotive supplier factory. Cable harness assembly involves multiple stages in which operators prepare modules for assembly boards and establish correct cable connections based on schematic diagrams. Nevertheless, due to the complexity of the modules and the similarity among cables, operators may have difficulty interpreting schematics, spend excessive time locating the correct connector positions, and consequently make assembly errors. Within the scope of the study, an AR-supported application developed using the Unity platform will allow operators to view step-by-step guidance for correct cable connections through a tablet interface. The proposed system is expected to accelerate the adaptation process of newly hired operators while reducing the difficulties experienced by experienced workers when transitioning to new projects. Furthermore, the study aims to facilitate error correction, reduce losses during assembly board and testing stages, prevent material waste, and lower overall production costs.

Keywords

Augmented Reality, Cable Assembly, Industrial Training, Simulation, Automotive Industry.

1. Introduction

With the advent of Industry 4.0, manufacturing systems have undergone a substantial transformation driven by digitalization, cyber-physical systems, and the increasing integration of human-machine interaction. As one of the key enabling technologies of this transformation, augmented reality (AR) facilitates the seamless integration of digital information into physical production environments, thereby providing operators with real-time and context-aware assistance (Nee et al. 2012; Wang et al. 2016). Through AR technology, operators can access task-relevant information directly within their field of view, which significantly enhances decision-making processes and operational efficiency.

In complex manufacturing environments, assembly operations represent a critical component in terms of both time and cost. The high proportion of assembly within total production costs, combined with its susceptibility to human error, necessitates continuous improvement of these processes (Boothroyd et al. 2010). Conventional training approaches are typically based on written instructions and on-the-job learning practices, which often result in prolonged training durations and variability in operator performance (Nee et al. 2012).

To address these limitations, AR-based guidance systems have been increasingly adopted in recent years across assembly, maintenance, and training applications. These systems enhance knowledge transfer by providing step-by-step visual instructions and interactive feedback, thereby reducing the cognitive load on operators (Tang et al. 2003; Hou et al. 2015). Previous studies have demonstrated that AR-assisted assembly applications can effectively reduce error rates while improving task completion times (Agati et al. 2020). Furthermore, AR has been shown to be applicable across multiple stages of the product lifecycle, including design, assembly planning, training, and maintenance (Nee et al. 2012).

This study aims to evaluate the effectiveness of a mobile AR-based training application developed for cable and connector assembly processes in an automotive manufacturing environment. Within the scope of the study, user experience data collected from existing operators were analyzed through a structured survey, while objective performance was assessed through time measurements conducted with newly recruited operators. By integrating both subjective and objective evaluation methods, this study provides a comprehensive analysis of the impact of AR-assisted training systems on learning performance and operational efficiency. The contribution of this work lies in its implementation within a real industrial setting and in the combined evaluation of user perception and measurable performance outcomes.

The remainder of the paper is organized as follows: Section 2 reviews the existing literature on AR applications in manufacturing and assembly processes. Section 3 presents the industrial case study and details the cable assembly process. Section 4 describes the proposed mobile AR application, including its technical framework, design approach, and findings from user surveys and time-based performance analysis. Finally, Section 5 concludes the study and discusses directions for future research.

2. Literature Review

Due to its capability to integrate real and virtual environments, AR has garnered significant research interest since the late 1990s and has been envisioned as a technology with a broad range of future applications (Azuma 1997). In industrial contexts, AR offers significant advantages by providing operators with real-time information and guidance during production processes, thereby enhancing productivity, reducing error rates, and improving training effectiveness (Kunkera et al. 2024). Owing to these capabilities, AR has emerged as a powerful tool for improving efficiency across multiple sectors.

A substantial body of literature has examined the applications of AR in both manufacturing and service industries. One of the early notable efforts, the ARVIKA project, demonstrated the potential benefits of AR applications in mobile maintenance processes; however, it also highlighted practical challenges associated with head-mounted displays and marker-based tracking systems (Friedrich 2002). Similarly, in the automotive industry, spatial augmented reality-based systems have been developed to assist operators by visualizing spot welding locations directly on vehicle surfaces, thereby enabling intuitive and direct guidance (Zhou et al. 2012).

Subsequent studies have increasingly focused on applying AR to more complex manufacturing problems. These include managing high-detail digital models, integrating virtual and real environments, supporting user training, providing technical assistance, and enabling virtual planning of assembly processes. Furthermore, the combined use

of physics-based modeling and constraint-based modeling has been identified as an effective approach to improving the accuracy and reliability of AR-supported systems (Gonzalez-Badillo et al. 2014). In maintenance and service applications, AR has also enabled experts to remotely analyze systems and perform fault diagnosis without being physically present on-site (Aschenbrenner et al. 2016).

A review of AR applications across various industries reveals that cable harness design and routing simulations—particularly in the aerospace sector—have a well-established research background. Prior studies have extensively explored cable layout design processes within virtual and augmented environments (Yang et al. 2019). AR-based visualization methods have been proposed to support cable assembly processes in spacecraft systems (Chen et al. 2019). Furthermore, the performance and usability of mobile AR glasses in manual wiring tasks for industrial panels have been evaluated through objective field experiments (Szajna et al. 2020). In parallel, intelligent cable assembly assistants supported by deep learning have been developed by integrating wearable AR devices with portable visual inspection mechanisms (Zheng et al. 2020). Collectively, these studies demonstrate that AR-based systems enhance the comprehensibility of assembly processes, improve accuracy, and reduce operational errors (Yang et al. 2021). Additionally, knowledge graph-based AR work instruction systems have been introduced for final cable harness assembly on formboards, enabling structured and context-aware guidance (Wang et al. 2023). Similarly, in the broader manufacturing domain, both commercial and customized AR-based solutions have been developed for applications such as quality control, assembly, and remote assistance (Grzegorzczuk and Śliwiński 2025). Recent trends in cable harness manufacturing highlight the growing importance of context-aware and cognitive AR assembly instructions, emphasizing their potential future contributions to operational efficiency (Fang et al. 2025). Moreover, in aircraft cable harness installation processes, mixed reality-based assistant systems have been utilized to optimize assembly error risks (Wang et al. 2025). In addition, novel AR-based work instruction integrations have been proposed to support the general training of operators in manufacturing environments (Malega et al. 2026). Despite these advantages, AR technology also presents several limitations, including high hardware and software costs, the complexity of development processes, and certain challenges related to user experience. In particular, issues such as cognitive distraction and reduced awareness of the physical environment have been reported in some applications.

From the perspective of the automotive industry, AR has demonstrated considerable potential in improving assembly operations. The visual and interactive guidance provided by AR enables complex assembly tasks to be performed more efficiently and with fewer errors. For instance, projector-based spatial AR systems developed for manual welding operations have been shown to enhance operational accuracy by visually highlighting welding points (Doshi et al. 2017). Additionally, automated optical inspection systems have been introduced to improve quality control processes in wire harness manufacturing, thereby increasing traceability (Nguyen et al. 2021). Other studies have focused on developing error-prevention mechanisms specifically for wire harness assembly processes (Li et al. 2024). More recent research indicates that AR-based assembly systems have become increasingly intelligent and interactive, incorporating real-time feedback and error detection mechanisms that continuously monitor the positional accuracy of components and provide instant guidance to users. Such systems have been shown to reduce cognitive load, enhance user experience, and significantly decrease error rates (Correia et al. 2026).

In addition to academic research, the adoption of AR technologies for optimizing cable assembly processes has been rapidly expanding in industrial practice through commercially available solutions. Major software providers such as Zuken have developed modules that integrate augmented reality into complex wire harness manufacturing processes (Zuken n.d.). Similarly, global electrification and cable manufacturer Nexans has actively employed AR applications as a key tool in its industrial transformation initiatives (Nexans 2026). Likewise, Siemens offers integrated systems that combine electrical system design with AR-based training solutions (Siemens Digital Industries Software 2026), while spatial augmented reality companies such as LightGuide aim to standardize operator workflows and training processes through projection-based guidance systems (LightGuide Inc. 2026).

In the context of studies conducted in Türkiye, AR applications in the automotive sector have predominantly focused on correct part selection and reducing cognitive workload (Turan 2019). However, despite the advancements in both national and international literature, a significant portion of existing academic and commercial solutions still rely on either high-cost hardware investments—such as projection systems and smart glasses—or complex industrial data infrastructures. In particular, AR-based applications that are specifically designed for assembly training, compatible with existing mobile infrastructures, cost-effective, and capable of generating real-time error logs to provide dynamic feedback during the training process remain relatively underexplored in terms of practical field integration. This gap

highlights an important opportunity for developing scalable and accessible AR training solutions tailored to real-world manufacturing environments.

This study aims to facilitate faster adaptation of newly recruited operators to cable assembly processes, reduce error rates, and improve the transition efficiency of experienced operators during new product introductions. Through the developed mobile AR-based system, it is intended to enhance both learning performance and operational accuracy within assembly processes. Accordingly, it is anticipated that AR technology will not only contribute to increased productivity in the automotive industry but also significantly improve quality levels and overall competitiveness of manufacturing enterprises.

3. Industrial Case Description and Assembly Process

This study was conducted in an automotive supplier company manufacturing in-vehicle cable systems for commercial vehicles. The company supplies products to several major automotive manufacturers; however, company names are not disclosed due to data confidentiality agreements. The cable assembly operations carried out on the production line consist of a series of highly precise processes, most of which are performed manually. In order to provide a clear and representative explanation of the process, a sample assembly module (socket/connector) was selected. The general structure of the cable assembly systems used in the production line is illustrated in Figure 1.

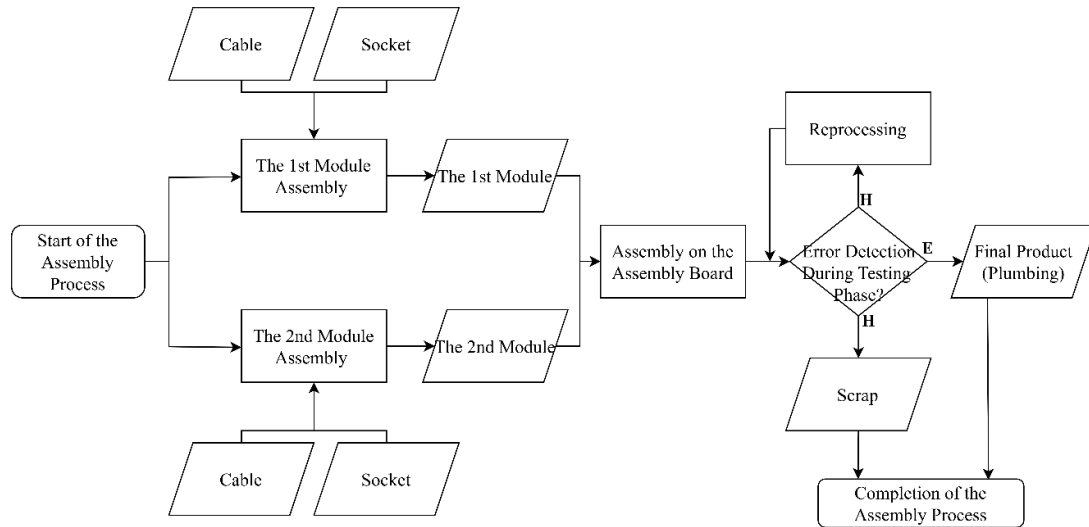


Figure 1. Assembly process flow diagram.

The assembly process consists of four main stages: (i) cable preparation, (ii) insertion into the connector, (iii) terminal crimping, and (iv) final inspection. Each of these stages is critical in terms of product quality and functional reliability. Proper execution of the process is essential to ensure electrical continuity and to deliver a defect-free final product to the customer.

Newly recruited operators are trained using conventional training methods. This training process includes printed work instructions, demonstrations by experienced operators, and on-the-job learning practices. An example of the traditional training and assembly guidance process is presented in Figure 2.

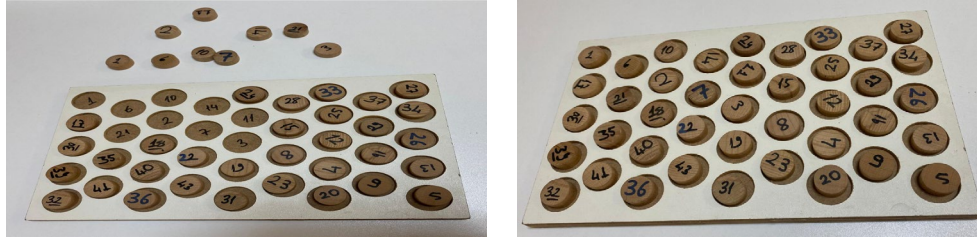


Figure 2. Traditional training method used in cable module assembly training.

As shown in Figure 2, a manual procedure based on matching numbered slots on a physical panel with corresponding numbered cable components is applied. The slots on the panel represent socket pins, while the numbered components correspond to the cables to be assembled. This approach aims to help operator trainees understand the fundamental logic of the assembly process.

However, process analyses and field observations have revealed that this conventional method has several pedagogical and operational limitations. In particular, the static and two-dimensional nature of the system makes it difficult for operators to fully comprehend complex and multi-step assembly processes. As a result, the learning process often shifts from conceptual understanding to memorization. Furthermore, the lack of real-time feedback and error warning mechanisms during the matching process leads to the reinforcement of incorrect practices and prolongs the time required for operators to develop correct working habits.

Although the traditional training approach is partially sufficient in conveying the basic principles of the assembly process, it fails to accurately represent the complexity of physical connection operations performed in real production environments. Therefore, to better understand the assembly process, it is necessary to examine the module-based physical assembly operations carried out on the production line in detail.

In this context, the vehicle wiring harness assembly process was analyzed through a representative module, and the main stages are described below. In the first stage, during module assembly, the designated cables are inserted into the corresponding sockets according to their properties such as number, color, and length, as shown in Figure 3(a), thereby forming the module. Operators determine which pins the cables should be connected to by referring to module diagrams, as illustrated in Figure 3(b). They leave the pins that should not be connected empty and apply sealing plugs where necessary. At this stage, correct placement of cables (Figure 3(c)) and complete execution of connections are crucial for the overall functionality of the electrical system. The difference between a correctly assembled module and an incorrectly assembled one—such as placing a cable in the wrong position (Figure 3(d))—clearly demonstrates the sensitivity of the process. Faulty modules may require rework in subsequent stages and can lead to serious failures in the vehicle's electrical system.

Following module assembly, the prepared modules are transferred to the assembly board for integration. At this stage, modules are positioned according to technical drawings, and interconnections between them are established. Additionally, taping operations are performed, and necessary accessories such as clips and covers are integrated into the system. Proper completion of these operations is essential for ensuring the mechanical robustness and organized structure of the wiring harness.

After the integration stage, the system proceeds to testing. In this phase, electrical continuity and current transmission performance of the completed harnesses are tested, and faulty connections are identified and corrected. Accessories are also checked for proper functionality, followed by a final visual inspection. Harnesses that successfully pass all tests are packaged and prepared for shipment.

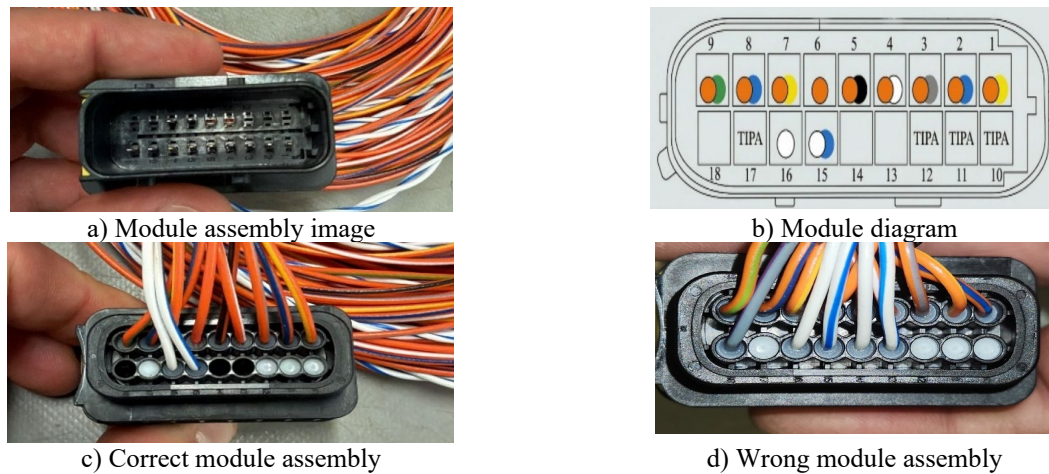


Figure 3. Example module diagram and correct vs. incorrect wiring configurations.

Field observations indicate that newly recruited operators particularly struggle with understanding module diagrams. The presence of a large number of cables and visually similar colors increases process complexity and raises the likelihood of incorrect connections. This situation prolongs operator adaptation time and leads to production delays. While reworking faulty modules negatively affects production efficiency, undetected defective harnesses reaching customers may result in severe financial losses. In some cases, customer-detected defects can even lead to the return of entire shipments.

To overcome these limitations, enhance the effectiveness of the training process, and improve operator performance, a mobile AR-based training simulation was developed. The proposed system reduces dependency on physical panels and instead provides a more dynamic, interactive, and real-time feedback-supported learning environment. In this way, it is aimed to both reduce error rates and accelerate operator adaptation processes.

4. Augmented Reality-Based Industrial Application Framework

In this section, the technical infrastructure, design approach, and implementation process of the mobile AR-based training system developed in this study are presented in detail. The system architecture, user interaction, and field applications are addressed collectively to establish a holistic framework.

4.1. AR System Architecture and Technology Selection

Within the scope of the proposed study, certain structural requirements arising from the nature of immersive technologies were taken into consideration during the software development process of the mobile AR application. According to the literature, the development of AR/VR technologies—whose integration into modern industrial processes is rapidly increasing—poses unique challenges during the design, implementation, and testing phases of the Software Development Life Cycle (SDLC). Key technical challenges include immersive experience design, the complexity of 3D interactions, cross-platform compatibility, and the reproducibility of errors (Bose and Brown 2024). Accordingly, the mobile AR application developed in this study was modeled by taking these technical constraints and SDLC requirements into account.

In line with this approach, both technical feasibility and industrial applicability were considered when defining system architecture. The system was structured around three main components: hardware infrastructure, software development environment, and digital content/modeling layer, as presented in Table 1.

Table 1. Components, sub-components, and example devices/platforms of the AR application.

Component	Sub-component	Example Platforms/Devices
Hardware	AR headsets, mobile devices	Microsoft HoloLens, Magic Leap, tablets, HDMI displays
Software	AR development kits	Unity, Vuforia, ARKit, ARCore
Data & Content	3D models	---

Within the scope of hardware selection, both AR headsets and mobile devices were evaluated. Although AR headsets (e.g., HoloLens and Magic Leap) provide a highly immersive experience (Schwald et al. 2001; Friedrich 2002; Ojer et al. 2020; Chu and Ko 2021; Grzegorzczuk and Śliwiński 2025), they present several disadvantages such as ergonomic risks during prolonged use (e.g., eye strain and headaches), operational limitations, and high costs. Therefore, in this study, tablet devices were preferred as a more accessible, cost-effective, and user-friendly solution. Tablets offer both mobility and flexibility in the learning process, making them a suitable alternative for industrial training scenarios (Friedrich 2002; Soon et al. 2015; Aschenbrenner et al. 2016; Alves et al. 2020).

Unity was selected as the software development environment. Thanks to its powerful graphics engine, extensive developer ecosystem, and AR Foundation infrastructure, Unity enables the development of cross-platform applications compatible with both Android and iOS devices (Chu and Ko 2021; Grzegorzczuk and Śliwiński 2025; Horejsi 2015; Ojer et al. 2020). This capability allowed for the effective integration of high-quality visualization, interactive interface design, and real-time feedback mechanisms.

On the digital content side, three-dimensional models of the physical components used in the training process were created and integrated into the system. In particular, a detailed 3D model of the socket (connector) structure—being the primary focus of the study—was developed to accurately represent the real assembly process within a digital environment.

4.2. Design of Augmented Reality Training Application

The developed mobile AR-based “Zero-Error” training simulation aims to enhance the training performance of newly recruited operators in cable module assembly processes within the automotive industry. The system provides an interactive learning environment that minimizes error rates while delivering real-time feedback to the user.

The application interface was designed to ensure ease of use and intuitive user experience. On the main screen, control buttons such as “Try Again” and “Exit”, along with functional buttons including “Run Test”, “Module Scheme”, and “Connect”, are positioned as shown in Figure 4. This structure enables users to manage the training process according to their individual learning pace.



Figure 4. Main user interface of the developed mobile AR simulation application and control buttons.

The “Connect” function represents the core interaction mechanism of the system, enabling users to place cables and sealing components into the correct pin locations. Through this process, users actively engage in learning by experiencing the digital equivalent of the physical assembly operation.

The “Module Scheme” function provides users with a technical reference diagram, allowing them to verify where each component should be connected. During the assembly process, users can access this function to visualize the module scheme and monitor their progress in real time, as illustrated in Figure 5. This feature reduces cognitive load—especially for novice operators—while minimizing the likelihood of operational errors. After reviewing the technical scheme, users can return to the main assembly interface via the “Close” button.

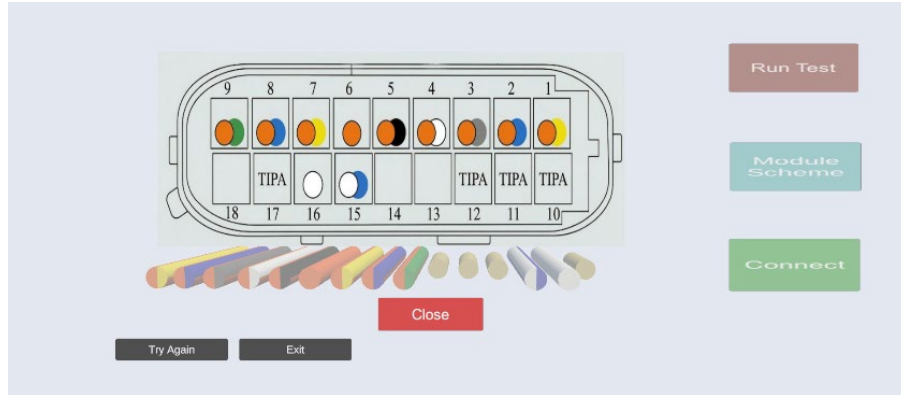


Figure 5. Integrated digital technical reference scheme for module assembly operations.

The “Run Test” function is one of the most critical components of the system, providing a feedback mechanism that analyzes the accuracy of the completed assembly. After completing all connections, the user activates this function to initiate the system’s real-time validation algorithm.

- **Correct assembly:** If all cables are matched with the correct pins, the corresponding pins on the socket are highlighted in green (see Figure 6). Simultaneously, performance outputs such as “CONNECTION LOGS: CORRECT” and “FALSE CONNECTIONS: 0” are displayed on the left panel.

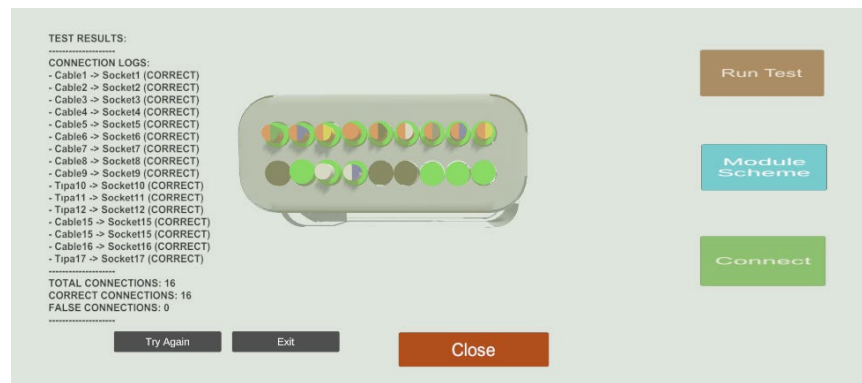


Figure 6. System feedback for *correct* assembly after “Run Test” validation.

- **Incorrect assembly:** In the case of incorrect connections, mismatched pins are highlighted in red, providing immediate visual feedback (see Figure 7). Additionally, the system generates a dynamic error log that compares the user’s connections with the correct configuration, explicitly indicating which cable is connected to which socket position and what the correct placement should be.

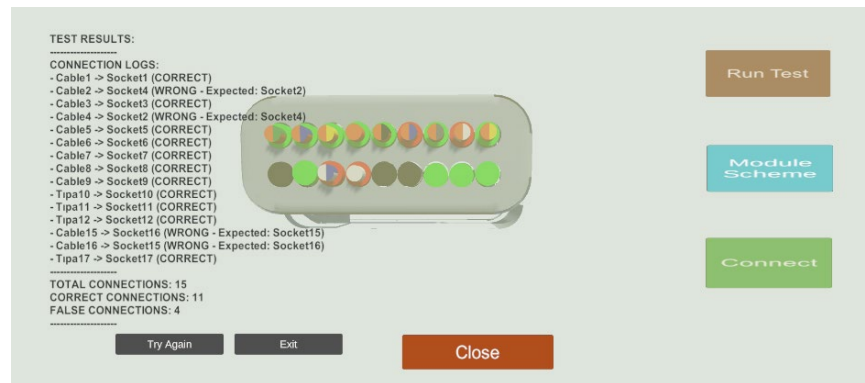


Figure 7. System feedback for *incorrect* assembly after “Run Test” validation.

Through this interactive and analytical structure, users can clearly identify the causes of their errors and reinforce their learning process. Users who perform incorrect operations can restart the simulation using the “Try Again” button or exit the training module via the “Exit” button.

This cyclical and experiential learning model offers a controlled trial-and-error-based training approach, aiming to minimize physical assembly errors on the production line. Consequently, it presents a sustainable and scalable augmented reality-based training methodology for industrial applications.



Figure 8. Testing of the developed mobile AR training application by operators in a factory environment.

4.3. Performance Evaluation and Statistical Assessment

The effectiveness of the developed mobile AR-based training system was evaluated through field experiments conducted in a real manufacturing environment (see Figure 8). The evaluation framework was designed as a two-stage approach, integrating both subjective and objective data in order to comprehensively assess the system’s impact on user experience and operational performance.

In the first stage, the demographic characteristics of the 14 participating operators were analyzed. The results indicated that 57.1% of the participants were between the ages of 25 and 34, while 92.8% had a high school education. Furthermore, 85.7% of the participants reported no prior experience with augmented reality technologies. In terms of work experience, 42.8% of the operators had more than five years of tenure. These findings demonstrate that the participant group represents a diverse user profile, including both experienced workers and individuals unfamiliar with emerging technologies, thereby strengthening the generalizability of the evaluation results.

Subsequently, a 16-item questionnaire based on a five-point Likert scale was administered to assess user experience. As presented in Table 2, the findings indicate high levels of satisfaction across all evaluated dimensions, including usability, learning effectiveness, perceived realism, training impact, and motivation. All category means exceeded 4.30, suggesting an overall positive perception of the AR-based training system among participants.

Table 2. User experience evaluation results of the AR-based training system.

Dimension	Mean (μ)	Standard Deviation (σ)
Usability	4.38	0.97
Learning Effectiveness	4.83	0.67
Realism	4.52	0.73
Training Impact	4.95	0.20
Motivation	4.98	0.09

Specifically, the usability dimension ($\mu = 4.38$, $\sigma = 0.97$) indicates that the system was generally perceived as easy to use, although the relatively higher standard deviation reflects individual differences in adaptation, likely due to the participants' limited prior exposure to AR technologies. In contrast, the learning effectiveness ($\mu = 4.83$, $\sigma = 0.67$) and realism ($\mu = 4.52$, $\sigma = 0.73$) dimensions yielded higher scores with lower variability, indicating that the 3D models and interactive environment effectively supported the learning process and successfully replicated real assembly operations.

The most notable results were observed in the training impact and motivation categories. The training impact dimension yielded a mean of $\mu = 4.95$ ($\sigma = 0.20$), while motivation achieved $\mu = 4.98$ ($\sigma = 0.09$). The very low standard deviation values in these categories indicate a strong consensus among participants, suggesting that the system was consistently perceived as an effective, engaging, and motivating training tool.

Table 3. Comparison of training and assembly times between conventional and AR-based methods.

Method	Measurement	Training Time (min)	Module Assembly Time (min)
Conventional Method	1st Measurement	3.07	2.19
	2nd Measurement	2.21	2.20
AR-Based Method	1st Measurement	1.31	2.05
	2nd Measurement	1.01	2.02

To objectively evaluate system performance, time-based analyses were conducted with four newly recruited operators. Training and module assembly durations using the conventional method and the AR-based system were compared, as shown in Table 3. The results reveal that the average training duration decreased from 2.64 minutes using the traditional method to 1.16 minutes with the AR-based application, corresponding to approximately a 56% reduction. This significant improvement indicates that AR support enables new operators to grasp assembly logic more rapidly and adapt more efficiently to the production process.

Similarly, improvements were observed in module assembly times. While the conventional method resulted in an average assembly duration of 2.20 minutes, this value decreased to 2.03 minutes with the AR system. Although the reduction is relatively modest, the decreased variability between measurements suggests more stable and consistent operator performance. This finding indicates that the AR-based system not only accelerates the training process but also enhances the reliability of assembly operations. Overall, when the survey findings and time analysis results are considered together, it is evident that the proposed mobile AR-based training system provides substantial benefits in terms of user satisfaction, learning performance, and operational efficiency. The results demonstrate that AR technology can serve as an effective support tool in cable assembly training within the automotive industry, particularly by facilitating faster adaptation for newly recruited operators.

5. Conclusions

This study comprehensively addresses the design, implementation, and evaluation of a mobile AR-based “zero-error” training system for cable harness assembly processes in the automotive sector. The proposed system aims to overcome the limitations of conventional training methods by providing operators with a real-time, visual, and interactive learning environment. The findings clearly highlight the effectiveness of AR technology in reducing error rates, accelerating learning processes, and improving operational efficiency in complex assembly tasks.

Both subjective and objective results confirm the high performance of the system. While survey outcomes indicate that users perceive the system as highly beneficial, engaging, and effective, time analyses validate measurable improvements, including up to a 56% reduction in training duration and enhanced assembly performance. These results demonstrate that AR technology is not only a conceptual training tool but also a practical solution capable of delivering measurable productivity gains in real industrial environments. The primary contribution of this study lies in the implementation of a mobile AR system within an actual automotive production line and the combined evaluation of user perception and operational performance metrics.

Nevertheless, the study has certain limitations. The relatively small sample size and the fact that the experiments were conducted in a single production facility may limit the generalizability of the findings. Additionally, the evaluation focuses on short-term performance outcomes and thus does not fully capture long-term learning retention and behavioral changes. Future research should therefore consider larger sample sizes and diverse industrial settings to validate and extend these findings.

From a future research perspective, integrating artificial intelligence-based error prediction mechanisms, developing adaptive real-time learning models, and evaluating hybrid systems incorporating wearable devices represent promising directions. Moreover, long-term field studies assessing sustained performance improvements will be critical for the broader industrial adoption of AR-based training systems. Overall, this study demonstrates that the integration of AR technology into manufacturing training processes holds significant technical and operational potential within the scope of Industry 4.0 transformation.

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References

- Agati, S.S., Bauer, R.D., Hounsell, M.S. and Paterno, A.S., Augmented Reality for Manual Assembly in Industry 4.0: Gathering Guidelines, *Proceedings of the 22nd Symposium on Virtual and Augmented Reality (SVR)*, pp. 165-172, Porto de Galinhas, Brazil, November 7-10, 2020. <https://doi.org/10.1109/SVR51698.2020.00039>
- Alves, J., Marques, B., Dias, P. and Santos, B.S., Using Augmented Reality and Step by Step Verification in Industrial Quality Control, *Proceedings of the 3rd International Conference on Human Systems Engineering and Design: Future Trends and Applications (IHSED 2020)*, pp. 350–355, Pula, Croatia, September 22-24, 2020. https://doi.org/10.1007/978-3-030-58282-1_55
- Aschenbrenner, D., Maltry, N., Kimmel, J., Albert, M., Scharnagl, J. and Schilling, K., ARTab - using Virtual and Augmented Reality Methods for an improved Situation Awareness for Telemaintenance, *IFAC-PapersOnLine*, vol. 49, no. 30, pp. 204-209, 2016. <https://doi.org/10.1016/j.ifacol.2016.11.168>
- Azuma, R.T., A Survey of Augmented Reality, *Presence: Teleoperators and Virtual Environments*, vol. 6, no. 4, pp. 355–385, 1997. <https://doi.org/10.1162/pres.1997.6.4.355>
- Boothroyd, G., Dewhurst, P. and Knight, W.A., *Product Design for Manufacture and Assembly*, 3rd Edition, CRC Press, Boca Raton, 2010. <https://doi.org/10.1201/9781420089288>
- Bose, D.B. and Brown, C., An Empirical Study on Current Practices and Challenges of Core AR/VR Developers, *Proceedings of the 39th IEEE/ACM International Conference on Automated Software Engineering Workshops*, pp. 233-238, Sacramento, California, USA, October 27-28, 2024. <https://doi.org/10.1145/3691621.3694956>
- Chen, H., Chen, C., Sun, G. and Wan, B., Augmented Reality Based Visualization Method for Spacecraft Cable Assembly Process, *IOP Conference Series: Materials Science and Engineering*, vol. 612, no. 3, p. 032184, 2019. <https://doi.org/10.1088/1757-899X/612/3/032184>
- Chu, C.H. and Ko, C.H., An experimental study on augmented reality assisted manual assembly with occluded components, *Journal of Manufacturing Systems*, vol. 61, pp. 685-695, 2021. <https://doi.org/10.1016/j.jmsy.2021.04.003>
- Correia, H., Duque, D., Moane, S. and Vilaça, J., Interaction feedback and error detection mechanisms in the AR assembly system, *SSRN Electronic Journal*, Preprint, pp. 1-19, 2026. <https://dx.doi.org/10.2139/ssrn.6554167>

- Doshi, A., Smith, R.T., Thomas, B.H. and Bouras, C., Use of projector based augmented reality to improve manual spot-welding precision and accuracy for automotive manufacturing, *The International Journal of Advanced Manufacturing Technology*, vol. 89, pp. 1279–1293, 2017. <https://doi.org/10.1007/s00170-016-9164-5>
- Fang, W., Chen, L., Han, L. and Ding, J., Context-aware cognitive augmented reality assembly: Past, present, and future, *Journal of Industrial Information Integration*, vol. 44, p. 100780, 2025. <https://doi.org/10.1016/j.jii.2025.100780>
- Friedrich, W., ARVIKA-augmented reality for development, production and service, *Proceedings of the International Symposium on Mixed and Augmented Reality*, pp. 3-4, Darmstadt, Germany, October 1, 2002. <https://doi.org/10.1109/ISMAR.2002.1115059>
- Gonzalez-Badillo, G., Medellin-Castillo, H., Lim, T., Ritchie, J. and Garbaya, S., The development of a physics and constraint-based haptic virtual assembly system, *Assembly Automation*, vol. 34, no. 1, pp. 41–55, 2014. <https://doi.org/10.1108/AA-03-2013-023>
- Grzegorzczak, T. and Śliwiński, R., Impact of augmented reality technology on firms' competitiveness, Scientific Papers of Silesian University of Technology. Organization & Management/Zeszyty Naukowe Politechniki Śląskiej. Seria Organizacji i Zarządzanie, no. 238, pp. 1-19, 2025. <http://dx.doi.org/10.29119/1641-3466.2025.238.8>
- Hořejší, P., Augmented Reality System for Virtual Training of Parts Assembly, *Procedia Engineering*, vol. 100, pp. 699-706, 2015. <https://doi.org/10.1016/j.proeng.2015.01.422>
- Hou, L., Wang, X. and Truijens, M., Using Augmented Reality to Facilitate Piping Assembly: An Experiment-Based Evaluation, *Journal of Computing in Civil Engineering*, vol. 29, no. 1, p. 05014001, 2015. [https://doi.org/10.1061/\(ASCE\)CP.1943-5487.0000344](https://doi.org/10.1061/(ASCE)CP.1943-5487.0000344)
- Kunkera, Z., Željko, I., Mimica, R., Ljubenkov, B. and Opetuk, T., Development of Augmented Reality Technology Implementation in a Shipbuilding Project Realization Process, *Journal of Marine Science and Engineering*, vol. 12, no. 4, pp. 550, 2024. <https://doi.org/10.3390/jmse12040550>
- Li, S., Yuan, M., Wang, W., Cao, F., Shi, H., Zhang, Y. and Meng, X., Enhanced YOLO- and Wearable-Based Inspection System for Automotive Wire Harness Assembly, *Applied Sciences*, vol. 14, no. 7, pp. 2942, 2024. <https://doi.org/10.3390/app14072942>
- LightGuide, Inc., Available: <https://lightguidesys.com/>, Accessed on June 19, 2026.
- Malega, P., Kováč, J., Leščinský, M. and Sabol, R., Augmented Reality as a Tool for Training Assembly Line Workers, *Applied Sciences*, vol. 16, no. 5, p. 2175, 2026. <https://doi.org/10.3390/app16052175>
- Nee, A. Y., Ong, S. K., Chrysosouris, G., and Mourtzis, D. Augmented reality applications in design and manufacturing, *CIRP Annals*, vol. 61, no. 2, pp. 657-679, 2012. <https://doi.org/10.1016/j.cirp.2012.05.010>
- Nexans, Available: <https://www.nexans.com/en/perspectives/a-new-reality-how-augmented-reality-is-transforming-industries-and-electrification>, Accessed on June 19, 2026.
- Nguyen, H.G. and Franke, J., Deep learning-based optical inspection of rigid and deformable linear objects in wiring harnesses, *Procedia CIRP*, vol. 104, pp. 1765-1770, 2021. <https://doi.org/10.1016/j.procir.2021.11.297>
- Ojer, M., Alvarez, H., Serrano, I., Saiz, F.A., Barandiaran, I., Aguinaga, D., Querejeta, L. and Alejandro, D., Projection-Based Augmented Reality Assistance for Manual Electronic Component Assembly Processes, *Applied Sciences*, vol. 10, no. 3, pp. 796, 2020. <https://doi.org/10.3390/app10030796>
- Schwald, B., Figue, J., Chauvineau, E., Vu-Hong, F., Robert, A., Arbolino, M., Schnaider, M., Laval, B., Raully, F., Gonzalez, F., Baldo, O. and Santos, J., STARMATE: Using augmented reality technology for computer guided maintenance of complex mechanical elements, *Proceedings of the international conference on industrial logistics*, pp. 135-142, 2001.
- Siemens Digital Industries Software, Available: <https://www.siemens.com/tr/tr.html>, Accessed on June 19, 2026.
- Soon, C.S., Ghazilla, R.A.R., Jen, Y.H. and Suen, P.Y., FRAMEWORK OF AUGMENTED REALITY APPROACH TOWARDS ERGONOMIC ASSESSMENT OF DRIVER VEHICLE PACKAGE DESIGN, *Jurnal Teknologi*, vol. 77, no. 27, pp. 31-37, 2015. <https://doi.org/10.11113/jt.v77.6903>
- Szajna, A., Stryjski, R., Woźniak, W., Chamier-Gliszczyński, N. and Kostrzewski, M., Assessment of Augmented Reality in Manual Wiring Production Process with Use of Mobile AR Glasses, *Applied Sciences*, vol. 10, no. 17, p. 5793, 2020. <https://doi.org/10.3390/app10175793>
- Tang, A., Owen, C., Biocca, F. and Mou, W., Comparative effectiveness of augmented reality in object assembly, *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems*, pp. 73-80, Fort Lauderdale, Florida, USA, April 5-10, 2003. <https://doi.org/10.1145/642611.642626>
- Turan, G., *Otomobil montaj hattında artırılmış gerçeklik gözlüğü kullanımının üretimde verimlilik üzerine etkisinin araştırılması*, Master's thesis, Fen Bilimleri Enstitüsü, Bursa Uludağ Üniversitesi, Bursa, Türkiye, 2019.

- Wang, X., Ong, S.K. and Nee, A.Y.C., A comprehensive survey of augmented reality assembly research, *Advances in Manufacturing*, vol. 4, pp. 1–22, 2016. <https://doi.org/10.1007/s40436-015-0131-4>
- Wang, J., Shi, T., Liu, M. and Jiang, K., Knowledge Graph Based Augmented Reality Work Instruction for Wire Harness Final Assembly on Formboard, *Proceedings of the 2023 IEEE 19th International Conference on Automation Science and Engineering (CASE)*, pp. 2487-2492, Auckland, New Zealand, August 26-30, 2023. <https://doi.org/10.1109/CASE56687.2023.10260511>
- Wang, Z., Li, W., Zhang, J., Zhou, Y., Chen, S., Dai, Y., Song, J., Cheng, Y. and Du, X., A mixed reality-based aircraft cable harness installation assistance system with fully occluded gesture recognition, *Robotics and Computer-Integrated Manufacturing*, vol. 93, p. 102930, 2025. <https://doi.org/10.1016/j.rcim.2024.102930>
- Yang, X., Liu, J., Lv, N. and Xia, H., A review of cable layout design and assembly simulation in virtual environments, *Virtual Reality & Intelligent Hardware*, vol. 1, no. 6, pp. 543-557, 2019. <https://doi.org/10.1016/j.vrih.2019.11.001>
- Yang, H., Li, S., Zhang, X. and Shen, Q., Research on Satellite Cable Laying and Assembly Guidance Technology Based on Augmented Reality, *Proceedings of the 40th Chinese Control Conference*, pp. 8116-8121, Shanghai, China, July 26-28, 2021. <https://doi.org/10.23919/CCC52363.2021.9550517>
- Zheng, L., Liu, X., An, Z., Li, S., and Zhang, R., A smart assistance system for cable assembly by combining wearable augmented reality with portable visual inspection, *Virtual Reality & Intelligent Hardware*, vol. 2, no. 1, pp. 12-27, 2020. <https://doi.org/10.1016/j.vrih.2019.12.002>
- Zhou, J., Lee, I., Thomas, B., Menassa, R., Farrant, A. and Sansome, A., In-Situ Support for Automotive Manufacturing Using Spatial Augmented Reality, *International Journal of Virtual Reality*, vol. 11, no. 1, pp. 33-41, 2012. <https://doi.org/10.20870/IJVR.2012.11.1.2835>
- Zuken, Augmented Reality for Wire Harness Assembly: An Innovative Matchup, Available: <https://www.zuken.com/us/blog/augmented-reality-for-wire-harness-assembly-an-innovative-matchup/>, Accessed on June 19, 2026.

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